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Theoretical Investigation of Steam and Air Mixtures

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THEORETICAL INVESTIGATION OF STEAM AND AIR MIXTURES

BY

GEORGE GLENN WILEY

THESIS

FOR THE

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IN

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

George Glenn Wiley,

ENTITLED Theoretical Investigation of Steam and Air Mixtures

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in

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Nomenclature.

All temperatures and pressures are absolute unless otherwise specified.

T_{1a}, Temperature of pure air after compression.

T_{2a}, Temperature of pure air before compression.

P_{1a}, Pressure to which air is compressed.

P_{2a}, pressure of air before compression.

K, Expansion exponent for pure air.

V_{1a}, Volume of free air after compression.

V_1, Volume of Steam-air Mixture before expansion

V_s, Volume of mixture at saturation of steam.

T_1, Temperature of mixture before expansion.

P_1, Pressure of mixture before expansion.

M_1, Weight of air in mixture in pounds.

M_2, Weight of steam in mixture in pounds.

B_1, Constant for Air, 0.37.

B_2, Constant for Steam, 0.5962.

C', Correction constant for volume of superheated steam, 0.256

P_{1s}, Original pressure of pure steam.

T_s, Temperature of steam at pressure, P_{1s}.

P_1'', Partial pressure of steam before expansion.

P_1', Partial pressure of air before expansion.

T_1'', Temperature of saturated steam at pressure, P_1''.

T_1', Temperature of air at pressure, P_1'.

S_1'', Entropy of steam in mixture before expansion.

S_1', Entropy of air in mixture before expansion.

S_1, S_m } Entropy of the mixture.

C, constant whose log = 13.64592

P_s, pressure of steam before mixing.

ΔU_a, Energy of pure air after compression.

ΔU_s, Energy of pure steam before mixing.

ΔU_m, Energy of unexpanded mixture.

C_v, Specific heat of air at constant volume.

C_p, Specific heat of air at constant pressure.

D, Degree of superheat of the steam in the mixture.

x, quality of the steam in the mixture.

e_2, Entropy of the liquid when mixture is below the point of saturation of the steam in the mixture

V_1'', Volume of saturated steam in region where the steam in the mixture is below saturation.

n, Expansion exponent for mixture.

W_{12}, Work of expansion of the mixture.

W_c, Work of compression of the air.

W_n, Net work of card available.

J, Number of Foot-pounds equivalent to 1 Btu.

Q_1, Heat equivalent of W_n.

Q_s, Heat supplied to the steam.

η_T, Thermal Efficiency, %.

Theoretical Investigation of Steam and Air Mixtures

The purpose of this paper is to present a carefully prepared theoretical discussion of the ideal engine cycle for a mixture of steam and air. It has been stated that a mixture of steam and air will give a thermal efficiency higher than that of pure steam. This statement is based upon the fact that in the mixture the partial pressure of the steam is reduced and that this reduction increases the available energy of the steam in the mixture. This assumption is true if only the expansion of the mixture is considered but a part of the available energy of the steam must be used to compress the pure air before it is mixed with the steam. This will diminish the net available energy of the steam in the mixture and now the question arises as to whether the increase in available energy of the steam in the mixture overbalances the work of compression of the air or not. If it does the above mentioned theory is true and if it does not, the above mentioned theory is not true. As heretofore stated, the purpose of this paper is to clearly present the theoretical discussion of this question.

When free air is compressed adiabatically, it follows the law expressed by the equation;

$$T_{1a} = T_{2a}\left(\frac{P_{1a}}{P_{2a}}\right)^{\frac{K-1}{K}} \quad \text{---------- (1)}$$

When P_{1a}, P_{2a} and T_{2a} are known, T_{1a} is readily determined.

After the air is compressed to the pressure P_{1a}, it is mixed with saturated steam at the same pressure. The temperature of saturated steam at this pressure is lower than that of air and hence the temperature of the mixture will lie between the temperature of pure saturated steam and pure air. Just where the mixture temperature will fall will depend on the percentage of air in the mixture; that is, the greater the percentage of air in the mixture, the nearer T_{1a} the mixture temperature will be.

When air is compressed adiabatically to P_{1a}, its final volume is expressed by the equation;

$$V_{1a} = \frac{M_1 B_1 T_{1a}}{P_{1a}} \quad \text{---------- (2)}$$

The volume of saturated steam is determined from either the steam-tables or from the equation for superheated steam, considering saturated steam as steam with 0° of superheat. This equation is.

$$V_s = \frac{M_2 B_2 T_s}{P_{1s}} - C' \quad \text{---------- (3)}$$

The two gases are mixed at constant volume and hence the mixture volume is equal to the volume of the air plus the volume of saturated steam, or

$$V_1 = V_{1a} + V_s \quad \text{---------- (4)}$$

The mixture temperature is determined by applying the energy equations of pure air and steam because the energy of the mixture is equal to the sum of the energy of the steam and the energy of the air. The temperature of the pure air before mixing is given by equation 1. The energy of the air is determined by the equation,

$$AU_a = M_1 C_v T_{1a} \text{ ---------- } ⑤$$

The energy of the steam is determined either from the steam tables or from the equation for superheated steam, considering saturated steam as steam with 0 degrees of superheat. This equation is,

$$AU_s = M_2 T_s (e + f T_s) - \frac{C P_s}{T_s^5} + 886.7 \text{ ---------- } ⑥$$

Since the energy of the mixture is equal to the sum of the energies of its constituents,

$$AU_m = AU_a + AU_s \text{ ---------- } ⑦$$

or

$$AU_m = M_1 C_v T_{1a} + M_2 T_s (e + f T_s) - \frac{C P_s}{T_s^5} + 886.7 \text{ ---------- } ⑧$$

Equation ⑧ gives the energy of the mixture from the energies of each of the free constituents. This must be changed so that it will give the energy of the mixture in terms of the mixture temperature since this temperature is desired. T_{1a} and T_s may be replaced by T_1, the mixture temperature and P_s may be replaced by the partial pressure of the steam.

Since the volume of the mixture is known, equation ④, the partial pressure of the steam in the mixture is determined by the equation,

$$P_1'' = \frac{M_2 B_2 T_1}{V_1 + C'} \text{ - - - - - - - - - - } ⑨$$

Substituting P_1'' for P_s and T_1 for T_{1a} and T_s, equation ⑧ then reads in terms of the mixture, or

$$AU_m = M_1 c_v T_1 + M_2 T_1 (e + f T_1) - \frac{C M_2 B_2}{(V_1 + C') T_1^4} + 886.7 \text{ - - - } ⑩$$

By representing the constants, $\frac{C M_2 B_2}{V_1 + C'}$ by a single constant, C'', then the equation ⑩ reads,

$$AU_m = M c_v T_1 + M_2 T_1 (e + f T_1) - \frac{C''}{T^4} + 886.7 \text{ - - - - } ⑪$$

AU_m is known from equation ⑦ and by trial the value of T_1 may be found by equation ⑪.

From equation ⑨, the partial pressure of the steam in the mixture is determined and the partial pressure of the air in the mixture is determined from the equation,

$$P_1' = \frac{M_1 B_1 T_1}{V_1} \text{ - - - - - - - - - - - } ⑫$$

The sum of the partial pressure of the air in the mixture and the partial pressure of the steam in the mixture gives the mixture pressure, P_1. or

$$P_1 = P_1' + P_1'' \text{ - - - - - - - - - - } ⑬$$

The mixture pressure is always a little less than the original pressure of free steam and free air on account of the chemical relations of the

molecules in the mixture. Still it is near enough to be used as a check on the original mixture volume.

The volume, V_1, is occupied by both gases on account of the process of diffusion. This is why V_1 is used in determining the partial pressures of the steam and the air. The reduction of the pressure on the steam in the mixture causes causes it to be superheated. The degree of superheat is determined thus: from the mixture temperature, T_1, subtract the temperature of saturated steam at a pressure equal to the partial pressure of the steam in the mixture, or,

$$\text{Degree of Superheat} = T_1 - T_1'' \qquad (14)$$

Figure I shows the change in the state of the steam on the Temperature-Entropy diagram when it is mixed with the air. Before mixing the steam is in the state represented by B. After mixing, the temperature of the steam rises from T_1'' to T_1, the pressure falls from P_{1s} to P_1'' and the new state of the steam after mixing is represented by the point C. The entropy is increased from S_s to S_1''. The exact path along which the steam moves in passing from state B to state C is not known.

The entropy is the next property of the mixture to be considered since during adiabatic expansion, the entropy remains constant. Since the air in the mixture and the steam in the mixture may be kept apart and each property of the two gases determined separately, then the entropy of each gas in the mixture may be determined separately. In the mixture both gases have the same temperature but each gas has a partial pressure of its own. The entropy of the mixture is the sum of the entropies of its constituents if each occupied the total volume separately and since an entropy can be determined for both the steam in the mixture and the air in the mixture, these two must be added to find the entropy of the mixture; that is,

$$S_m = S_s + S_a \qquad (15)$$

During adiabatic expansion of the mixture, S_m remains constant and if during expansion, the entropy of the steam in the mixture changes, that of the air in the mixture must change in the opposite way and to exactly an equal extent so that their sum will be equal to the entropy of the original mixture. Let S_1'' represent the original entropy of the steam in the

mixture and S_2'' that at any other point above saturation of the steam in the mixture. Let S_1' represent the original entropy of the air in the mixture and S_2' that of the air corresponding to S_2'' of the steam. Then the change of entropy of the steam in the mixture from state 1 to state 2 will be given by the expression, $S_1'' - S_2''$, and the change of the entropy of the air in the mixture will be shown by the expression, $S_1' - S_2'$. Since the sum of the entropies of each constituent in each state must equal S_m, the following equations are given:

$$S_1'' + S_1' = S_m \text{ (for state 1)}$$

$$S_2'' + S_2' = S_m \text{ (for state 2)}$$

or $$S_1'' + S_1' = S_2'' + S_2'$$

Collecting entropies of each gas,

$$S_1'' - S_2'' = -S_1' + S_2'$$

or $$S_1'' - S_2'' = -(S_1' - S_2') \quad \text{(16)}$$

This equation shows that the change of the entropy of the air is equal and opposite to the change of entropy of the steam in the mixture. This equation may be used as follows,

$$S_1'' - S_2'' + S_1' - S_2' = 0 \quad \text{(17)}$$

Equation (17) is the form of the equation that represents the adiabatic expansion of the mixture. For superheated steam the entropy equation is,

$$S = a \log T + bT - d \log p - p(1+ep)\frac{c}{T^6} - 0.3964. \quad \text{(18)}$$

By writing equation (18) for S_1'' and from this subtract the same for S_2'', in each case using the mixture temperatures, T_1 & T_2 respectively and the partial pressures of the steam, P_1'' and P_2'' respectively, there is obtained an equation for $S_1'' - S_2''$, which is part of the expansion equation (17). The change of entropy of air in the mixture is given by the equation,

$$S_1' - S_2' = C_p \log_e \frac{T_2}{T_1} - AB \log_e \frac{P_2}{P_1}. \quad \text{---} \quad (19)$$

By substituting the mixture temperatures T_1 and T_2 respectively, changing the logarithmic base to base 10 and substituting the respective partial pressures of the air, P_1' and P_2', then adding equation (19) to equation representing $S_1'' - S_2''$, there is obtained an expansion equation in terms of P, V and T; or

$$S_1'' - S_2'' + S_1' - S_2' = a \log \frac{T_1}{T_2} + b(T_1 - T_2) - d \log \frac{P_1''}{P_2''} - P_1''(1 + \epsilon P_1'') \frac{C}{T_1^6}$$
$$+ P_2''(1 + \epsilon P_2'') \frac{C}{T_2^6} + 2.306 M_1 C_p \log \frac{T_2}{T_1} - 2.306 M_1 AB \log \frac{P_2'}{P_1'}. \quad \text{---} \quad (20)$$

By substituting for P_2'' and P_2' expressions obtained from the equations,

$$P_2'' = \frac{M_2 B_2 T_2}{V_2 + C'} \quad ; \qquad P_2' = \frac{M_1 B_1 T_2}{V_2}$$

and solving algebraically, the following equation is obtained;

$$2.306 M_1 AB \log V_2 - M_2 d \log (V_2 + C') = (M_2 a - 2.306 M_1 C_p) \log T_2$$
$$+ M_2 b T_2 - M_2 d \log (M_2 B_2 T_2) + 2.306 M_1 AB \log (M_1 B_1 T_2) - \frac{M_2 B}{V_2 + C'} \left(1 + \epsilon \frac{M_2 B_2 T_2}{V_2 + C'}\right) \frac{C}{T_2^5} - K_1 \quad \text{---} \quad (20)$$

where $K_1 = a \log T_1 + bT_1 - d \log P_1'' - P_1''\left(1 + eP_1''\right)\frac{c}{T_1^6}$

$-M_1\left[2.306 M_1 C_p \log T_1 - 2.306 AB \log P_1'\right]$.

Equation (20) is a very long and difficult equation to handle and it is much easier to solve the adiabatic expansion in the region of superheat of steam in the mixture by the "cut and try" method.

The "cut and try" method just mentioned is carried out in the following manner:- select a mixture temperature and an approximate partial pressure of the steam in the mixture for that temperature. From the steam tables get the temperature of saturated steam at the chosen partial pressure. Subtract this saturation temperature from the chosen mixture temperature and the remainder will be the degree of superheat of the steam in the mixture. Then from the superheated steam tables find the entropy of the steam in the mixture and the volume of the mixture. The mixture volume will be equal to the volume of the steam in the mixture because both the steam and the air occupy the same volume. Then from equation (12) determine the partial pressure of the air in the mixture, P_2'. The sum of the two partial pressures gives the mixture pressure. Determine the entropy of the air in the mixture by means of the equation,

$$S_2' = C_p \log_e T_2 - AB \log_e P_2' \text{ — — — — — } (21)$$

The sum of the entropy of the air in the mixture just obtained and the entropy of the steam in mixture obtained from the superheated steam tables should be equal to the original entropy of the mixture. If not, hold the chosen temperature and select another partial pressure for the steam in the mixture and repeat the method just described. In reselecting the approximate partial pressure, the following key is useful; if the sum of the two partial pressures is greater than the original mixture pressure, select a lower partial pressure of the steam in the mixture for the next trial. After two or three trials have been made, the true partial pressure for the steam in the mixture for the chosen temperature may be found by plotting a curve with entropy and partial pressure as co-ordinates. Then with this true partial pressure, repeat the process for accurate results.

Below saturation of steam in the mixture, the same general equation holds, that is,

$$S_1'' - S_2'' + S_1' - S_2' = 0 \text{ — — — — — } (22)$$

As before, equation (19) is substituted for the change of air in the mixture, $S_1' - S_2'$. For the entropy of the steam, the following equation is

used, $$S = e + \frac{x r}{T} \quad \text{---------} \quad (23)$$

in which e is the entropy of the liquid, T is the temperature of the mixture, r is the latent heat of vaporization at temperature T and x is the quality of the steam in the mixture. From this equation the partial entropy of the steam in the mixture at state 2 is,

$$S_2'' = e_2 + \frac{x r_2}{T_2} \quad \text{---------} \quad (24)$$

Since S_1'' is known in state 1, then

$$S_1'' - S_2'' = S_1'' - \left(e_2 + \frac{x r_2}{T_2}\right) \quad \text{-----} \quad (25)$$

By adding the expressions for the changes of the partial entropies according to equation (22) the adiabatic expansion equation for the mixture below the point of saturation of steam in the mixture is obtained, or

$$0 = S_1'' - \left(e_2 + \frac{x r_2}{T_2}\right) + 2.306\, M_1 \left(C_p \log \frac{T_2}{T_1} - AB \log \frac{P_2'}{P_1'}\right) \quad (26)$$

By substituting the ratio for x,

$$x = \frac{V_1}{V_1''} \quad \text{---------} \quad (27)$$

and solving algebraically with the aim of separating the logarithmic functions of the volume from the direct functions the following equation is derived,

$$2.306\, M_1 AB \log V_2 = K_1 - 2.306\, M_1 C_p \log T_2 +$$

$$2.306\, M_1 AB \log \frac{.37 M_1 T_2}{P_1'} - M_2 \frac{r_2 V_2}{T_2 V_2''} - M_2 e_2 \quad \text{-----} \quad (27)$$

in which K_1 has the following value,

$$K_1 = M_2 S_1'' + 2.306\, M_1 C_p \log T_1$$

Equation (27) is a transcendental equation and is solved by placing each side equal to y and then plotting curves with y and V_2 as co-ordinates. When T_2 is chosen and the y curves plotted, their intersection will give a value for V_2, the volume of the mixture at the temperature T_2. By use of the steam tables V_2'', the volume of saturated steam at temperature T_2, will be found. Then x, the quality of the steam in the mixture is determined according to equation (27).

The adiabatic expansion curve of the mixture is divided into two parts, as heretofore mentioned. In fitting an equation to this curve, each part must be considered separately because each part follows a separate equation. However both equations are of the form,

$$PV^n = C' \qquad (28)$$

but in each equation the exponent n and the constant C' change. These variables are found by the method of least squares, as follows; — Written logarithmically, equation (28) becomes

$$\log P + n \log V = C \qquad (29)$$

where C is the logarithm of C' in equation (28). Select three or four points along the expansion curve either all above or all below the point of saturation of the steam in the mixture and

substitute the logarithms of these points for log P and log V in equation (29). Form a new equation by the following method. Multiply each equation by the coefficient of one of the unknown terms in the equation, using the same unknown term in each equation. Add these new equations and their sum will give one equation. Repeat this operation by using the other unknown term. The sum of this second set of new equations will give a second equation. Hence two equations, each having two unknown terms have been developed from several equations, each having the same two terms unknown. Solve these two equations algebraically for the two unknown terms. For example let $x = \log P$ and $y = \log V$, then

$$x + ny = C.$$

For different points chosen, subscript x & y,

$$x_1 + ny_1 = C$$

$$x_2 + ny_2 = C$$

$$x_z + ny_z = C$$

adding, $(x_1 + x_2 \cdots + x_z) + n(y_1 + y_2 -- + y_z) = zC. - - - (30)$

In this case the coefficient of $C = 1$ and hence the first operation is accomplished by simply adding the equations. Multiply each equation by the coefficient of n in the equation,

$$x_1 y_1 + n y_1^2 = y_1 C$$

$$x_2 y_2 + n y_2^2 = y_2 C$$

$$x_z y_z + n y_z^2 = y_z C$$

adding; $(x_1 y_1 + x_2 y_2 \cdots + x_z y_z) + n\left(y_1^2 + y_2^2 \cdots + y_z^2\right) = (y_1 + y_2 \cdots + y_m) C$ (31)

In equations (30) and (31) each point has equal weight and the algebraic solution of these two equations gives the unknowns, n and C.

The value of n may be determined by another method and the one will serve as a check on the other. Plot the values of P and V on logarithmically co-ordinated paper. While n is constant these points will fall in a straight line. As above let $x = \log P$ and $y = \log V$. Select two points and make up the following equations

$$x_1 + n y_1 = C$$

$$x_2 + n y_2 = C$$

Subtract; $(x_1 - x_2) + n(y_1 - y_2) = 0$

or $n(y_1 - y_2) = x_2 - x_1$

and $n = \dfrac{x_2 - x_1}{y_1 - y_2}$

substituting the proper values for x & y,

$$n = \frac{\log P_2 - \log P_1}{\log V_1 - \log V_2} \quad \text{---------} \quad (32)$$

In other words, n is the slope of the curve as it is drawn on logarithmically co-ordinated paper. When the whole expansion curve is drawn upon this kind of co-ordinates, it takes the form of

two intersecting straight lines. The point where the intersection occurs represents the point where saturation of the steam in the mixture occurs during expansion. The fact that the curve lies in two straight lines when plotted in these co-ordinates shows very clearly that there is a different n for each part of the expansion curve. Figure 11 shows a series of these curves. In these curves the percentage of air in the mixture is varied but the weight of the percentage of steam in the mixture is kept constant throughout. Fig. 10 shows the curves that represent the variation of n as the percentage of air in the mixture is varied for both above and below saturation of the steam in the mixture. For the variation of n above saturation of steam in the mixture, an emperical equation has been found which is,

$$n = 1.34 - 0.0018x + 0.000025x^2 \qquad (33)$$

in which x is the percentage of air in the mixture. For the region below saturation of steam in the mixture, no satisfactory equation can be worked out for the variation of n.

The Working Cycle

For steam and air mixtures the following cycle is traversed;- Pure air, at atmospheric pressure and temperature, is adiabatically compressed to a pressure equal to the pressure of the steam. This process forms the compression line of the card. After being compressed, steam is admitted to the air until the ratio between the steam and air in the mixture is at an all ready fixed ratio. This process forms the admission line on the card. Then the mixture is allowed to expand adiabatically until the mixture pressure is atmospheric pressure. There is no exhaust line to the working cycle for steam and air mixtures because the mixing is practically, an irreversible process. No actual chemical action takes place but the water that comes from the condenser would have to be corrected because the air leaving the condenser would be saturated with water and hence it would not be pure air. So the exhaust line of the working cycle is omitted and the process of separating the steam and air is considered practically impossible-

Thermal Efficiency of the Cycle.

The Thermal Efficiency of steam and air mixtures is defined thus:- The heat equivalent of the effective work done divided by the heat supplied to the steam in the mixture, no heat being supplied to the air. The work done during an adiabatic expansion in which the value of the exponent n is constant is given by the equation,

$$W_{12} = \frac{n}{n-1}\left(P_1V_1 - P_2V_2\right) \text{ - - - - - - - - - - } (34)$$

For steam and air mixtures, this equation must be changed to comply with the change of the exponent n below the saturation of steam in the mixture. This is done by writing equation (34) for the region above saturation of steam in the mixture and to this add the same for the region below saturation of steam in the mixture, or

$$W_{12} = \frac{n_1}{n_1-1}\left(P_1V_1 - P_sV_s\right) + \frac{n_2}{n_2-1}\left(P_sV_s - P_2V_2\right) \text{ - - - } (35)$$

which gives the total work of expansion of the mixture. But the work of compression of the free air must be subtracted from the total work of expansion in order to obtain the net work of the card. The work of compression of the air is given by the

equation,

$$W_c = \frac{K}{K-1}\left(P_2V_2 - P_1V_1\right) \text{ — — — — — — — — } (36)$$

Then the net work of expansion is given by the expression,

$$W_n = W_{12} - W_c$$

or

$$W_n = \frac{n_1}{n_1-1}\left(P_1V_1 - P_sV_s\right) + \frac{n_2}{n_2-1}\left(P_sV_s - P_2V_2\right) - \frac{KM_1}{K-1}\left(P'_{2_a}V'_{2_a} - P_{1_a}V_{1_a}\right) \text{ — — } (37)$$

In order to determine the thermal efficiency, the heat equivalent of W_n must be obtained and this is obtained by dividing W_n by J, the number of footpounds that one British Thermal unit is equivalent to, or

$$Q_1 = \frac{W_n}{J} \text{ — — — — — — — — } (38)$$

Q_1 is then the heat equivalent of the effective work done during the expansion of the mixture and is the output of the mixture. The input is the heat supplied to the steam in the mixture since no heat is supplied to the air. This heat supplied is equal to the total heat of the steam at the mixing pressure minus the heat of the liquid of the steam at the partial pressure of the steam when the mixture is exhausted, or

$$Q_s = Q' - q_2'' \text{ — — — — — — } (39)$$

This expression gives the heat supplied to the steam in the mixture and since this is all

that is expended in producing the above output, Q_1, the thermal efficiency is the ratio between Q_1 and Q_s, or

$$\eta_T = \frac{Q_1}{Q_s} \text{ — — — — — — — —} (40)$$

Sample Calculations.

The calculations for the 80% air mixture will be given for a set of sample calculations. In order to have a basis for calculation, some original conditions must be assumed. Following are the assumed conditions:

Pressure of air before compression 14.7 lbs. per square inch absolute.

Temperature of air before compression, 65°F.

Steam pressure 250 lbs per square inch absolute.

The air is compressed until it has a pressure of 250 lbs. per. sq. in. abs., then it is mixed with the steam. After mixing, the mixture is adiabatically expanded until the mixture pressure is 14.7 lbs. per sq. in. abs. These conditions assume that the system is working without a condenser and that there is a back pressure of one atmosphere on the engine. A condenser would be impracticable since the large percentage of air would make condensation almost impossible, and would interfer greatly with the maintenance of a vacuum.

The first calculation to be made is the temperature of pure air after compression.

From equation ①,

$$T_{1a} = T_{2a}\left(\frac{P_{1a}}{P_{2a}}\right)^{\frac{K-1}{K}}$$

or since the above conditions were assumed,

$$T_{1a} = 525\left(\frac{250}{14.7}\right)^{\frac{1.4-1}{1.4}} = 525(17.006)^{0.2859}$$

Solving, $T_{1a} = 1180.3°$ absolute.

For a set of sample calculations the 80% air mixture calculations will be given. Four pounds of air to one of steam produces this percentage. Four pounds of air at 1180.3° and 250 lbs. per sq. in. pressure is mixed with saturated steam at the same pressure. The temperature of steam at 250 lbs pressure is 861.1° absolute, hence the mixture temperature will lie between 861.1 and 1180.3°. The energy of the mixture is the same as that of its constituents before mixing, hence the energies of the free constituents must be obtained. Equation ⑤ gives the energy of the air,

$$\Delta U_a = M_1 C_v T_{1a}$$

or $$\Delta U_a = 4 \times .171 \times 1180.3 = 809.68 \text{ Btu.}$$

The energy of one pound of steam, as given in the steam tables, at 250 lbs. per sq. in pressure is 1116.4 Btu., hence since $\Delta U_m = \Delta U_a + \Delta U_s$,

$$\Delta U_m = 809.68 + 1116.4$$

or $\Delta U_m = 1926.08$ Btu.

The volume of the mixture is equal to the volume of the steam at P_s plus that of the air at P_a. From the Steam Tables, V_s, the volume of pure steam at P_s is 1.850 cu. ft. The volume of the air is determined by equation 2, or

$$V_a = \frac{M_1 B_1 T_{1a}}{P_a} = \frac{4 \times .37 \times 1180.3}{250} = 6.98 \text{ cu. ft.}$$

Hence the mixture volume, V_1, is,

$$V_1 = V_a + V_s = 6.98 + 1.85 = 8.83 \text{ cu. ft.}$$

The mixture temperature is obtained from equation (11), or

$$AU_m = M_1 C_v T_1 + M_2 T_1 (e + f T_1) - \frac{C''}{T_1^4} + 886.7$$

The symbols e and f are equal to 0.256 and 0.00005 respectively. The constant C" is derived thus: In equation (10) there appears a term $\frac{C M_2 B_2}{(V_1 + c') T^4}$ which is derived from the expression $\frac{C P_s}{T^5}$ in equation 8.

$$\frac{C M_2 B_2}{(V_1 + c') T^4} = \frac{C \times 1 \times .5962}{(8.83 + 0.256) T^4} = \frac{C''}{T^4}$$

where $\log C = 13.64592$. By solving through this expression, the value of $\log C'' = 12.46295$

By substituting the symbolic values in equation (11) and solving algebraically, the following relation is obtained,

$$4 \times .171 \times T_1 + T_1 (0.256 + 0.00005 T_1) - \frac{C''}{T^4} = 1926.08 - 886.7$$

or $$0.9420 T_1 + 0.00005 T_1^2 - \frac{C''}{T^4} = 1039.38.$$

Choosing the value 1045 and 1050 for T_1 and solving it is found that T_1 lies between these two. By interpolating, $T_1 = 1047.6°$ absolute.

The partial pressure of the air in the mixture is determined by use of equation (12),

or $P_1' = \frac{4 \times .37 \times 1047.6}{8.83} = 175.59$ lbs. per sq. in.

That of the steam in the mixture is, from equation (9),

$P_1'' = \frac{1 \times .5962 \times 1047.6}{8.83 + .256} = 68.74$ lbs. per sq. in..

Since the mixture pressure is equal to the sum of the partial pressures of its constituents,

$P_m = 175.59 + 68.74 = 244.33$ lbs per sq. in..

The entropy of the mixture is the next property to be determined. In order to obtain this, the entropies of each constituent must be determined. In the steam there is superheat and the amount is found by subtracting the saturation temperature of steam at the partial pressure P_1'' from the mixture temperature, or

$$D = T_1 - T_1''$$

or $D = 1047.6 - 761.74 = 285.86°$

Using the steam tables it is found that the entropy of one pound of steam at pressure 68.74 lbs. per sq. in. and with 285.86° of superheat is 1.7901. The entropy of the air in the mixture is determined by the equation,

$$S_a = M_1 2.306 (C_p \log T_1 - AB \log P_1')$$

or $S_a = 4 \times 2.306 (0.24 \times 3.02019 - 0.0685 \times 2.24449)$

or $S_a = 5.2677$

Since $S_m = S_s + S_a$, $S_m = 1.7901 + 5.2677 = 7.0578$

After the entropy of the mixture was determined, the mixture was adiabatically expanded to the point where saturation of the steam in the mixture occurred, by the "cut and try" method. Following is the calculation for one of the conditions in the expansion:

Select a mixture temperature, $T_m = 857°$ absolute.

" " partial pressure of steam in mixture, $P_2'' = 32.75$ lbs. per sq. in. From the steam-tables $T_s = 715.4°$

$T_m = 857$

$T_s = \underline{715.4}$

$D = 141.6$ degrees of superheat in steam.

From Steam Tables, $V_m = 15.43$ cu. ft. and $S_s = 1.7790$.

From equation for S_a,

$$S_a = M_1 2.306 (C_p \log T_m - AB \log P_1'),$$

$$S_a = 5.2816$$

$S_m = S_a + S_s = 5.2816 + 1.7790 = 7.0606$.

This is so near that the assumed conditions may be taken as correct. S_m obtained in this way should equal S_m of the original mixture. The partial pressure of the air in the mixture is obtained from the equation

$$P_2' = \frac{M_1 B_1 T_2}{V_2} = \frac{4 \times .37 \times 857}{15.43} = 82.20$$

$P_m = P_2' + P_2'' = 82.20 + 32.75 = 114.95$ lbs per sq. in..

Following is a table covering the expansion to the point of saturation of steam in the mixture.

The following tables show the calculated results for the 80% air mixture. Table I shows the results of the "cut and try" method of calculation for the region in which the steam in the mixture is superheated.
Table II shows the calculations for the left hand side of the equality sign of equation (27). Then, in order to solve the equation, a curve with V_2 and y as co-ordinates was plotted. Also calculations of Table III were used. Table III shows the horizontal method of recording results so that every step is shown. The temperatures were chosen and by means of the $V-V_2$ curve, the correct V_2 for that temperature was found.
Table IV is a collection of results calculated so that they will be together for reference.
Table V is used in connection with the determination so it is placed with the calculations of that determination.

TABLE I

T_2	P_2''	P_2'	P_m	V_m	T_s	Degree of Superheat	S_2''	S_2'	S_m
1047.6	68.74	175.59	244.33	8.83	761.74	285.86	1.7901	5.2677	7.0578
952	48.7	121.98	170.68	11.55	739.4	212.6	1.7838	5.2757	7.0595
857	32.75	82.2	114.95	15.43	715.4	141.6	1.7790	5.2816	7.0606
762	22.0	54.56	76.56	20.67	693.1	68.9	1.7752	5.2823	7.0575
666	13.03	33.53	46.56	29.95	666	0.	1.7662	5.2864	7.0526.

TABLE II.

V_2	$\log V_2$	$\log\log V_2$	$\log(2.306 M.AB \log V_2)$	y
30.0	1.47712	0.16940	T.97000	0.9332
33.93	1.50356	0.17712	T.97772	0.9500
35.0	1.54406	0.18864	T.98924	0.9755
40.0	1.60206	0.20466	0.00526	1.0122
43.1	1.63447	0.21335	0.01395	1.0326
47.0	1.67209	0.22326	0.02386	1.0565
50.0	1.69897	0.23016	0.03076	1.0734
55.0	1.74036	0.24062	0.04122	1.0996
60.0	1.77815	0.24995	0.05055	1.1234
70.0	1.84509	0.26601	0.06661	1.1657
80.0	1.90309	0.27946	0.08006	1.2024
90.0	1.95424	0.29096	0.09156	1.2347
100.0	2.00000	0.30103	0.10163	1.2637

TABLE III

T_2 absolute	666	650	640	630	620	610	600
T_2 ° Fahr	206	190	180	170	160	150	140
$\log T_2$	2.82347	2.81291	2.80618	2.79934	2.79239	2.78532	2.77815
$\log \log T_2$	0.45077	0.44915	0.44811	0.44704	0.44597	0.44487	0.44374
$\log(2.306\ M_1 C_p \log T_2)$	0.79589	0.79427	0.79323.	0.79216	0.79109	0.78999	0.78886
$2306\ M_1 C_p \log T_2$	6.2502	6.2269	6.2120	6.1967	6.1815	6.1659	6.1498
$\log(.37\ M_1 T_2)$	2.99409	2.98317	2.97680	2.96996	2.96301	2.95594	2.94841
$\log\left(\frac{.37 M_1 T_2}{P_1'}\right)$	1.46855	1.45763	1.45126	1.44442	1.43747	1.43040	1.42287
$\log\log\left(\frac{.37 M_1 T_2}{P_1'}\right)$	0.16687	0.16363	0.16172	0.15968	0.15759	0.15545	0.15314
$\log(2.306\ M_1 AB \log \frac{.37 M_1 T_2}{P_1'})$	$\bar{1}.96747$	$\bar{1}.96423$	$\bar{1}.96232$	$\bar{1}.96028$	$\bar{1}.95819$	$\bar{1}.95605$	$\bar{1}.95374$
$2.306\ M_1 AB \log \frac{.37 M_1 T_2}{P_1'}$	0.9278	0.9209	0.9169	0.9126	0.9082	0.9037	0.8989
$M_2 e_2$	0.3027	0.2783	0.2628	0.2470	0.2311	0.2149	0.1984
r_2	974.1	983.9	989.9	995.8	1001.6	1007.4	1 013.1
$\log(M_2 r_2)$	2.98860.	2.99295	2.99559	2.99817	3.00069	3.00320	3.00565
V_2''	29.95	40.91	50.15	62.00	77.20	96.90	122.8
$\log V_2''$	1.47639	1.61182	1.70027	1.79239	1.88761	1.98632	2.08919
$\log(V_2''\ T_2)$	4.29986	4.42473	4.50645	4.59173	4.68000	4.77164	4.86734
$\log \frac{M_2 r_2}{V_2'' T_2}$	$\bar{2}.68874$	$\bar{2}.56822$	$\bar{2}.48914$	$\bar{2}.40644$	$\bar{2}.32069$	$\bar{2}.23156$	$\bar{2}.13831$
$\frac{M_2 r_2}{V_2'' T_2}$	0.0488	0.0370	0.0308	0.0254	0.0209	0.0170	0.0137
V_2	29.95	36.38	43.15	51.35	61.4	74.0	90.0
P_2''	13.03	9.34	7.51	5.99	4.73	3.71	2.88
P_1'	33.53	26.45	22.02	18.15	14.98	12.20	9.86
P_m	46.56	35.79	29.53	24.14	19.71	15.91	12.74
Quality of steam, %	100	88.9	86.0	82.9	79.5	76.4	73.2

TABLE IV

P_m absolute	V_m cu. ft.	T_m absolute	Degree of superheat	Quality
244.33	8.83	1047.6	285.86	———
170.68	11.55	952.0	212.60	———
114.95	15.43	857.0	141.60	———
76.56	20.67	762.0	68.90	———
46.56	29.95	666.0	0.0	100.0
35.79	36.38	650.0	———	88.9
29.53	43.15	640.0	———	86.0
24.14	51.35	630.0	———	82.9
19.71	61.40	620.0	———	79.5
15.91	74.00	610.0	———	76.4
12.74	90.00	600.0	———	73.2

Determination of Exponent n and Constant C' by the Theory of Least Squares for the Region in which the Steam in the Mixture is Superheated.

Table V

P_m	log P_m	V_m	log V_m	n log V_m	C − n log V_m	P_{m_2}	Difference
244.33	2.38797	8.83	0.94596	1.28365	2.38811	244.41	+0.08
170.68	2.23218	11.55	1.06258	1.44190	2.22986	169.77	−0.91
114.95	2.06050	15.43	1.18836	1.61262	2.05914	114.49	−0.46
76.56	1.88400	20.67	1.31534	1.78483	1.88693	77.07	+0.51
46.54	1.66801	29.95	1.47639	2.00805	1.66371	46.10	−0.46

$PV^n = C'$ or written logarithmically,

$\log P + n \log V = C$, where $C = \log C'$.

Substituting values from above table in logarithmic equation,

$$2.38797 + n\,0.94596 = C$$
$$2.23218 + n\,1.06258 = C$$
$$2.06050 + n\,1.18836 = C$$
$$1.88400 + n\,1.31534 = C$$
$$1.66801 + n\,1.47639 = C$$

Adding, $10.23266 + n\,5.98863 = 5C$ ---------- a

Multiplying each equation by coefficient of n in equation,

$$2.25885 + n\,0.89483 = 0.94596\,C$$
$$2.37190 + n\,1.12907 = 1.06258\,C$$
$$2.44870 + n\,1.41230 = 1.18836\,C$$
$$2.47800 + n\,1.73000 = 1.47639\,C$$
$$2.46260 + n\,2.17975 = 1.31534\,C$$

Adding, $12.02005 + n\,7.34595 = 5.98863C$ ------ b

From equation a,

$$C = \frac{10.23266 + 5.98863n}{5}$$

$$= 2.04653 + 1.19772n. \text{ ---- } c$$

From equation b, substituting above value of C,

$$12.02005 + 7.34595n = 5.98863(2.04653 + 1.19772n)$$

$$12.02005 + 7.34595n = 12.25560 + 7.17240n$$

$$0.17355n = 0.23555$$

$$n = 1.357.$$

Substituting in equation c,

$$C = 10.23266 + (1.19772 \times 1.357)$$

$$C = 3.67176$$

hence $C' = 4696.4$

By substituting the values of n and C' in the equation, $PV^n = C'$, an equation for the expansion of the superheated region of the 80% air mixture is obtained, or

$$PV^{1.357} = 4696.4$$

This equation satisfies all the points on the curve. In the table at the beginning of the determination of n, table V, the column headed P_{m_2} is calculated from this equation and it should be equal to the column P_m. In every case the difference is less than one pound per sq. in. as is seen by the column headed "difference".

For the region below the point of saturation of the steam in the mixture, the determination of the exponent n and the constant C' is the same as that for the superheated region. In this case the equation following is derived,

$$PV^{1.181} = 2613.9$$

This equation satisfies all the points to within one pound per square inch as does the superheated region's equation.

These equations show that for each region the mixture passes through, that is, the region in which the steam in the mixture is superheated and the region in which it is below saturation, the expansion law is expressed by the equation,

$$PV^n = C'$$

As the percentage of air in the mixture varies, the values of n and of the constant C' will vary also.

Now all necessary data for the calculation of the thermal Efficiency of the card has been determined. The net work of the card, W_n, is given by making the substitutions in equation (37)$_{11}$, or.

$W_n = \frac{n_1}{n_1 - 1}(P_1V_1 - P_sV_s) + \frac{n_2}{n_2 - 1}(P_sV_s - P_2V_2) - \frac{K M_1}{K - 1}(P_{2a}V_{2a} - P_{1a}V_{1a})$. By substituting, the following equation is obtained,

$W_n = \frac{1.44(1.357)}{1.357 - 1}(244.83 \times 8.8 - 46.56 \times 29.95) + \frac{1.44 \times 1.181}{1.181 - 1}(46.56 \times 29.95 - 14.7 \times 80) - \frac{4 \times 1.44 \times 1.4}{1.4 - 1}(14.7 \times 13.3 - 250 \times 6.98)$

Solving, $W_n = 139,183.484$ foot pounds.

The heat equivalent of W_n is,

$$Q_1 = \frac{W_n}{J} = \frac{139,183.484}{778} = 178.899 \text{ Btu.}$$

The heat supplied to the pound of steam in the mixture is determined by means of equation 39 and the Steam-tables,

$$Q_s = Q' - q'' = 1201.5 - 114 = 1087.5 \text{ Btu.}$$

The Thermal Efficiency is the ratio between Q_1 and Q_s or

$$\eta_T = \frac{Q_1}{Q_s} = \frac{178.899}{1087.5} = .1646 \text{ or } 16.46\%.$$

That is, only 16.46 % of the heat supplied to a pound of steam in an 80 % air mixture is available for useful work in the ideal case. In the practical case this value would be lower on account of radiation losses from the cylinder walls of the engine.

Tabulated Results.

The following table gives the calculated results for four mixtures, from which the curves were plotted:

% air.	25	50	75	80
T_1	880	935.7	1022.65	1047.4
P_{sm}	177.24	106.41	56.74	46.56
T_{sm}	815.8	757.7	686.8	666.0
P_1''	195.19	149.8	82.99	68.74
P_1'	44.62	96.4	159.37	175.59
P_1	239.81	246.2	242.36	244.33
P_s''	145.0	64.7	19.57	13.03
P_s'	32.24	41.97	37.17	33.53
P^s	177.24	106.67	56.74	46.56
P_a''	11.75	8.45	4.42	3.40
P_a'	2.95	6.25	10.28	11.80
n_1	1.31	1.319	1.356	1.357
n_2	1.142	1.141	1.138	1.181
Degree of Superheat.	40.1	117.3	248.05	285.86
V_1	2.432	3.555	7.089	8.830
V_s	3.12	6.68	20.51	29.95
V_a	27.5	37.5	66.5	80.0
S_m	2.0339	2.9746	5.6986	7.0578
η_T %	18.80	25.25	18.75	16.19

Discussion of the Variation of the Thermal Efficiency.

As seen by the calculated results and the curve, the maximum thermal Efficiency occurs when the mixture contains about 50% air by weight. In every mixture there is two opposing conditions; one tending to increase the efficiency and the other to diminish the same. As the percentage of air in the mixture is increased, the partial pressure of the steam at exhaust is diminished thereby making it possible to get more heat out of the steam. This is the condition that tends to increase the efficiency. The condition that tends to diminish the efficiency is the compressing of the air. As the percentage of air in the mixture increases, the percentage of steam in the mixture diminishes and since the steam is the heat supplying constituent, the heat supplied diminishes as the work of compression increases. In mixtures containing a low percentage of air, the exhaust partial pressure of the steam is high and in mixtures of high percentages of air, the work of compression of the air is large, both conditions tend to lower the thermal efficiency. These conditions allow an highest Thermal Efficiency when the mixture ratio by weight is approximately 1 to 1.

Investigation of Cards.

By simply looking at two cards, it might be thought that an higher percentage of air in the mixture would give an higher Thermal Efficiency. For example take two cards, Fig. 9A, one for the 50% air mixture and the other for the 80% air mixture. The steam in the mixture has a much lower saturation point in the 80% air mixture than in the 50%. The atmospheric volume of the 80% air card is much greater than that of the 50% air card. From this fact alone it might be thought that the 80% air card contained a larger area than the 50% card. But this 80% air card is drawn for 5 lbs. of mixture while the 50% air card is drawn for only two pounds. To eliminate this difference, draw the cards in the following manner, as shown in Fig. 9B. Draw a straight line along a line parallel to the constant volume line, to represent the compression line of the cards. Lay off horizontally from this line the horizontal differences between the compression and the expansion curves of the original cards. This gives cards that show the horizontal differences between the compression and the expansion lines of the original cards. It also gives a comparative

card that has three straight-line sides. The difference in area of the two cards is at once noticeable and the reason for such a difference is immediately seen. Above the point of saturation of steam in the 50% mixture, the two curves run along almost identically the same line. At the point of saturation of the 50% mixture, the 50% expansion curve slopes away from the vertical compression line and includes a greater area. The curve below the point of saturation of the 80% mixture slopes away and runs much more horizontally than the 50% curve but it does not include so much area as does the 50% card. It might be argued that the portions of the curves below ought to run very nearly horizontal since the values of the two expansion exponents, n, are very nearly equal. This argument would be true if the two curves were drawn from the same vertical co-ordinate but since the vertical compression line of the 80% card is four times as far from the y-axis as that of the 50% card, this argument fails.

Logarithmic Curves.

When the expansion curves for the mixtures are drawn on logarithmically co-ordinated paper, they fall in a series of straight lines. Fig. 11 shows these curves. Throughout these curves the percentage of steam by weight was held constant. The dotted line crossing the curves connect the points where saturation of steam in the mixture occurs. At this curve all the expansion curves change their direction a little showing that for each mixture the value of the exponent n in the equation $PV^n = C'$, changes when the point of saturation is crossed. The heavy line drawn across the curves on a constant pressure line is the atmospheric pressure line and indicates the point where expansion of the mixture ceases.

Throughout the series of mixtures the value of n changes in accordance with the percentage of air in the mixture. Figure 10 shows this curve. The heavy line represents the region above the point of saturation of steam in the mixture and the dotted line for the region below. The heavy line follows the equation, $n = 1.34 - 0.0018x + 0.000025x^2$.

Explanation of Figures and Curves.

Figure 1 shows the change of state of the steam when it is mixed with the air. The pure saturated steam is at state B. When mixed with air at the same pressure the state of the steam changes to C. Along what path it moves is unknown since heat content depends upon position instead of the path traversed.

Figure 2 represents the change of entropy of the steam during expansion below the point of saturation of the steam in the mixture. The mixture entropy is shown by the line Sm, which is equal to the sum of the entropy of the steam plus that of the air. The distance between S_1'' and Sm represents the entropy of the air in the mixture at the point of saturation of the steam in the mixture. V_2 represents any point below the point of saturation of the steam in the mixture.

Fig. 3 shows the variation of the absolute temperature of the mixture before expansion with the variation of the percentage of air in the mixture.

Figure 4 shows the relation between the percentage of air in the mixture and the temperature when saturation of steam in the mixture occurs. These points were determined by the "cut and try" method.

Figure 5 shows the variation of the pressure of the mixture at the saturation of steam in the mixture, with the percentage of air in the mixture. These points were calculated by the "Cut and Try" method.

Figure 6 shows the variation of the partial pressures of the steam and the air in the mixture before expansion, with the percentage of air in the mixture.

The two intersecting curves in Figure 7 show the variation of partial pressures of the steam and the air in the mixture, with the percentage of air in the mixture at the point where saturation of the steam in the mixture occurs. The curve P_2" shows the variation of the partial pressure of the steam in the mixture, with the percentage of air in the mixture at exhaust.

Figure 8 shows the variation of the volume of the mixture, with the percentage of air in the mixture at the following

points;

V_1 = volume of unexpanded mixture,

V_s = volume of mixture when saturation the steam in the mixture occurs,

V_2 = volume of the mixture at exhaust.

Throughout these curves, the percentage of steam by weight in each mixture equaled one pound.

Figure 9 shows the ideal engine cards for a steam and air medium. Figure B shows the difference in area of the two cards drawn in Figure A.

The full line in Figure 10 shows the variation of the exponent n, with the variation of the percentage of air in the mixture, for the region in which the steam in the mixture is superheated. The dotted line shows the same for the region in which the steam in the mixture is saturated.

Figure 11 shows the logarithmic expansion curves for the mixtures.

Figure 12 shows the variation of the thermal Efficiency of the mixture, with the variation of the percentage of the air in the mixture.

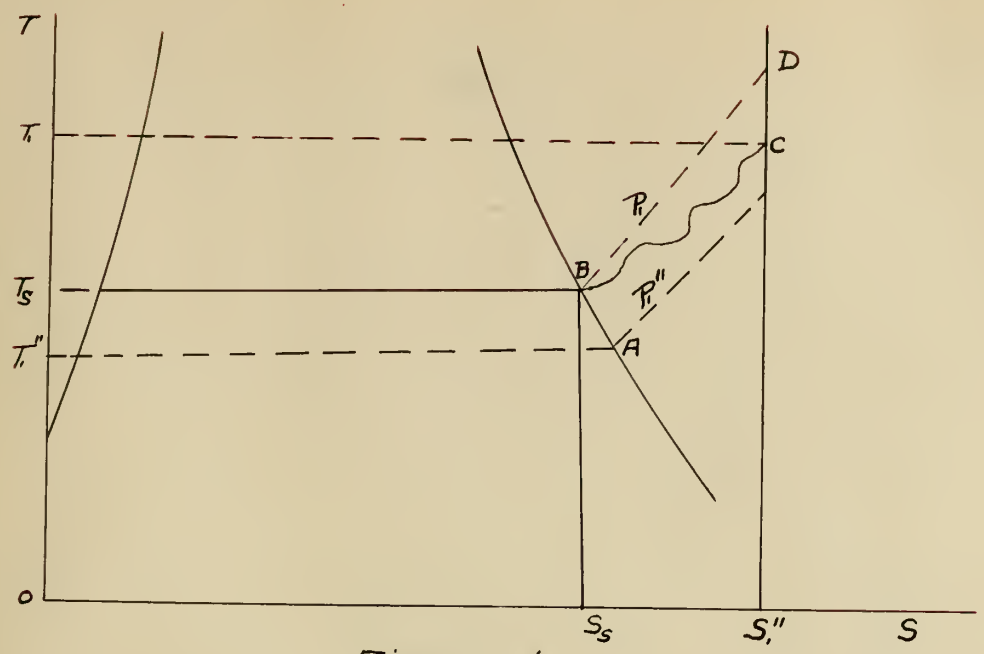


Figure 1

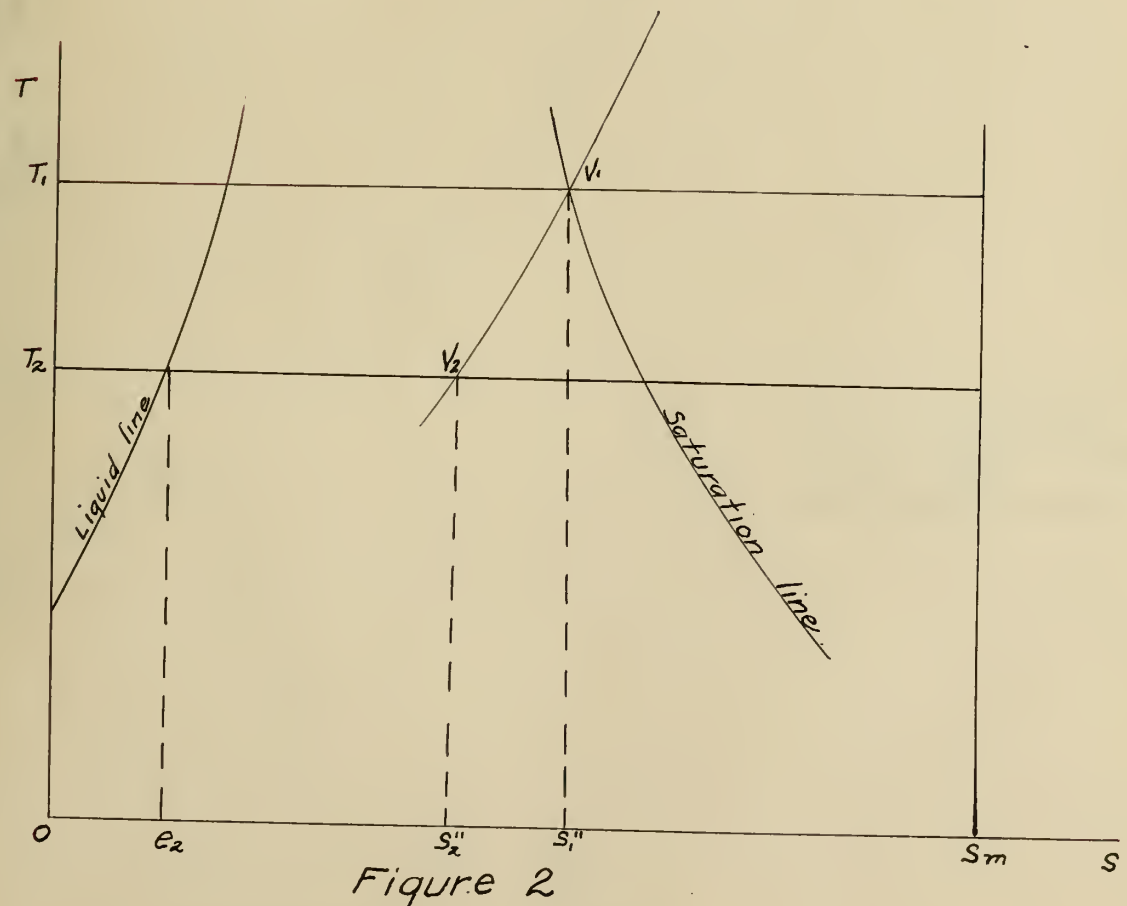
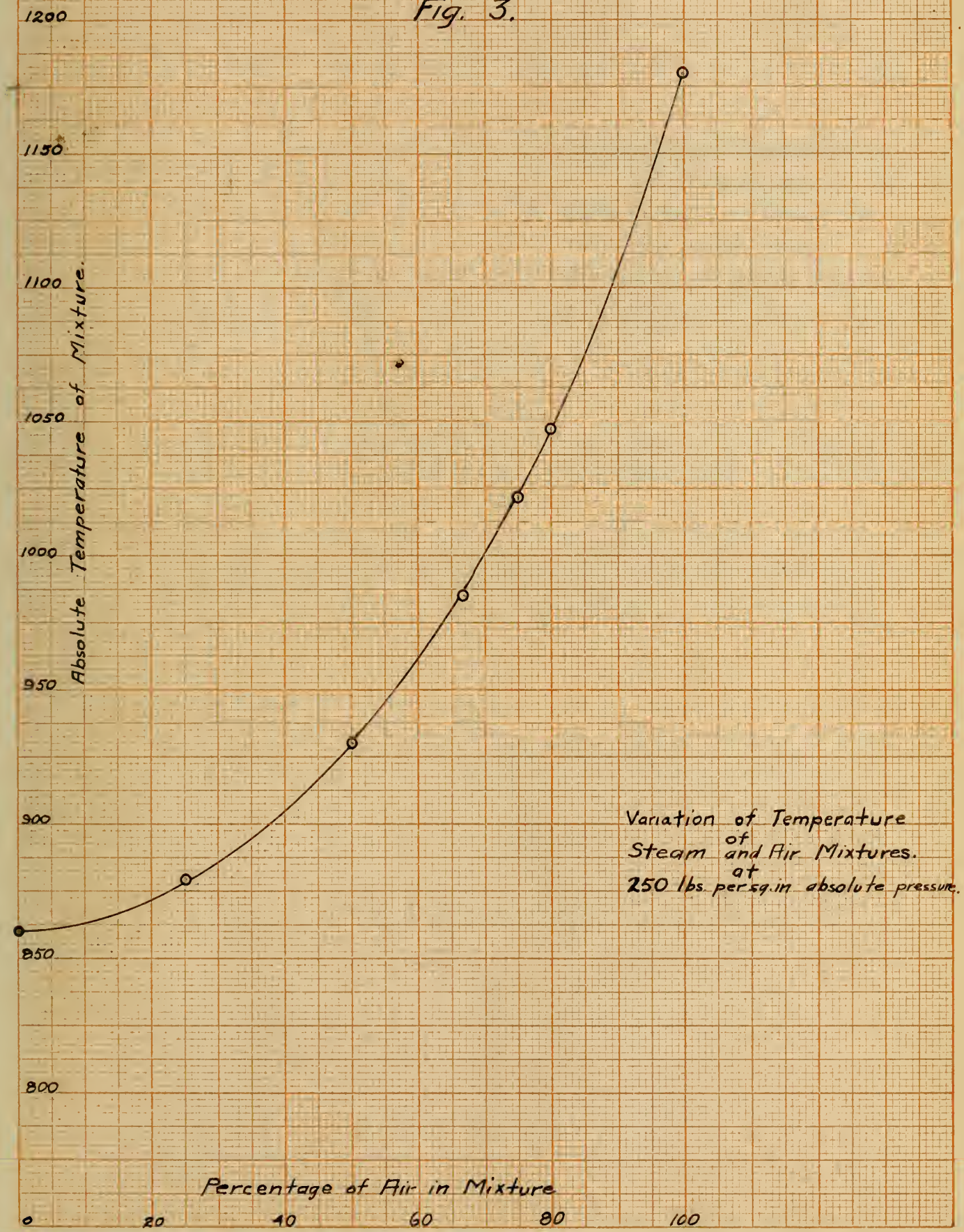


Figure 2

Fig. 3.



Variation of Temperature of Steam and Air Mixtures. at 250 lbs. per sq. in absolute pressure.

U. OF I. S. S. FORM 3

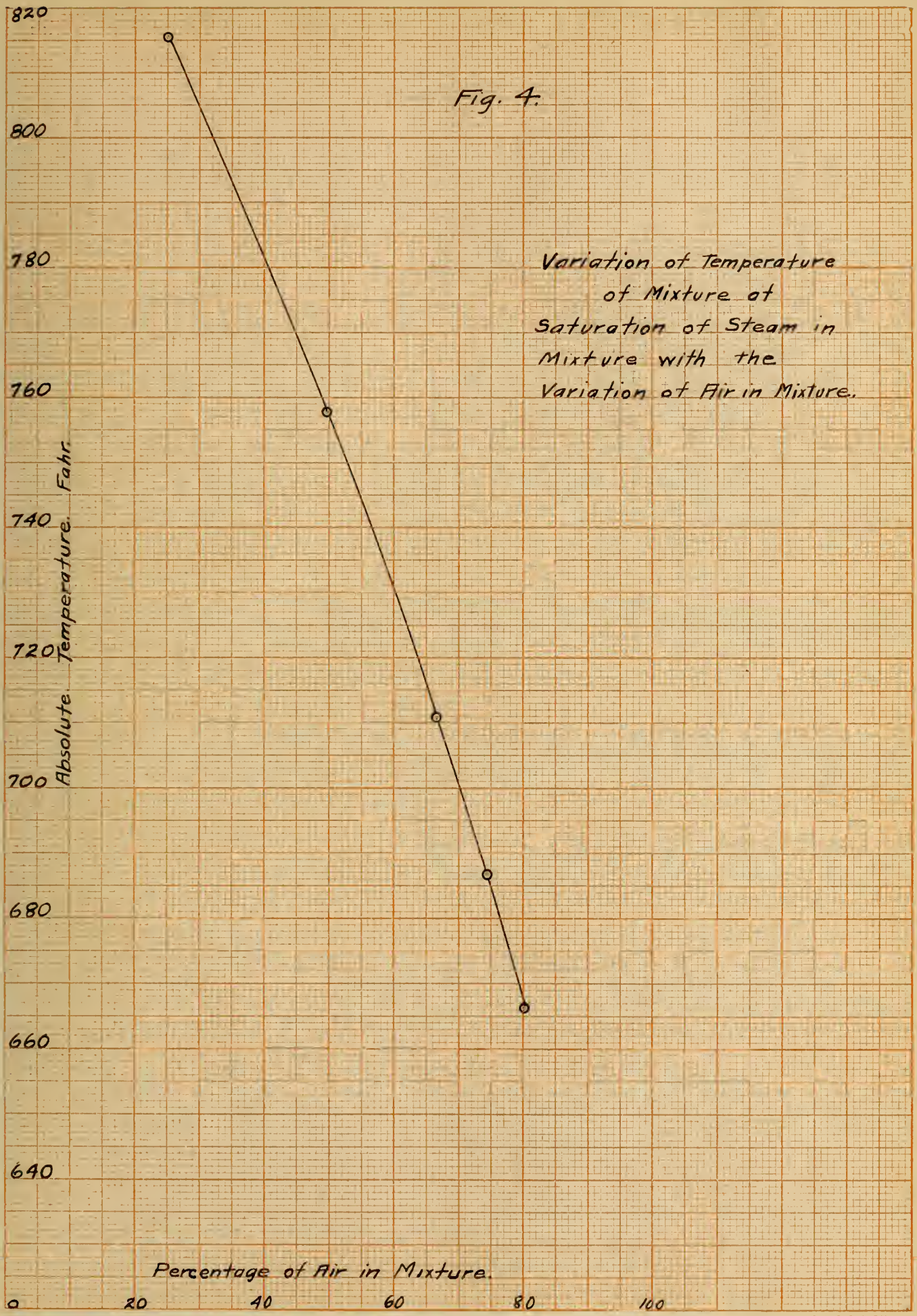
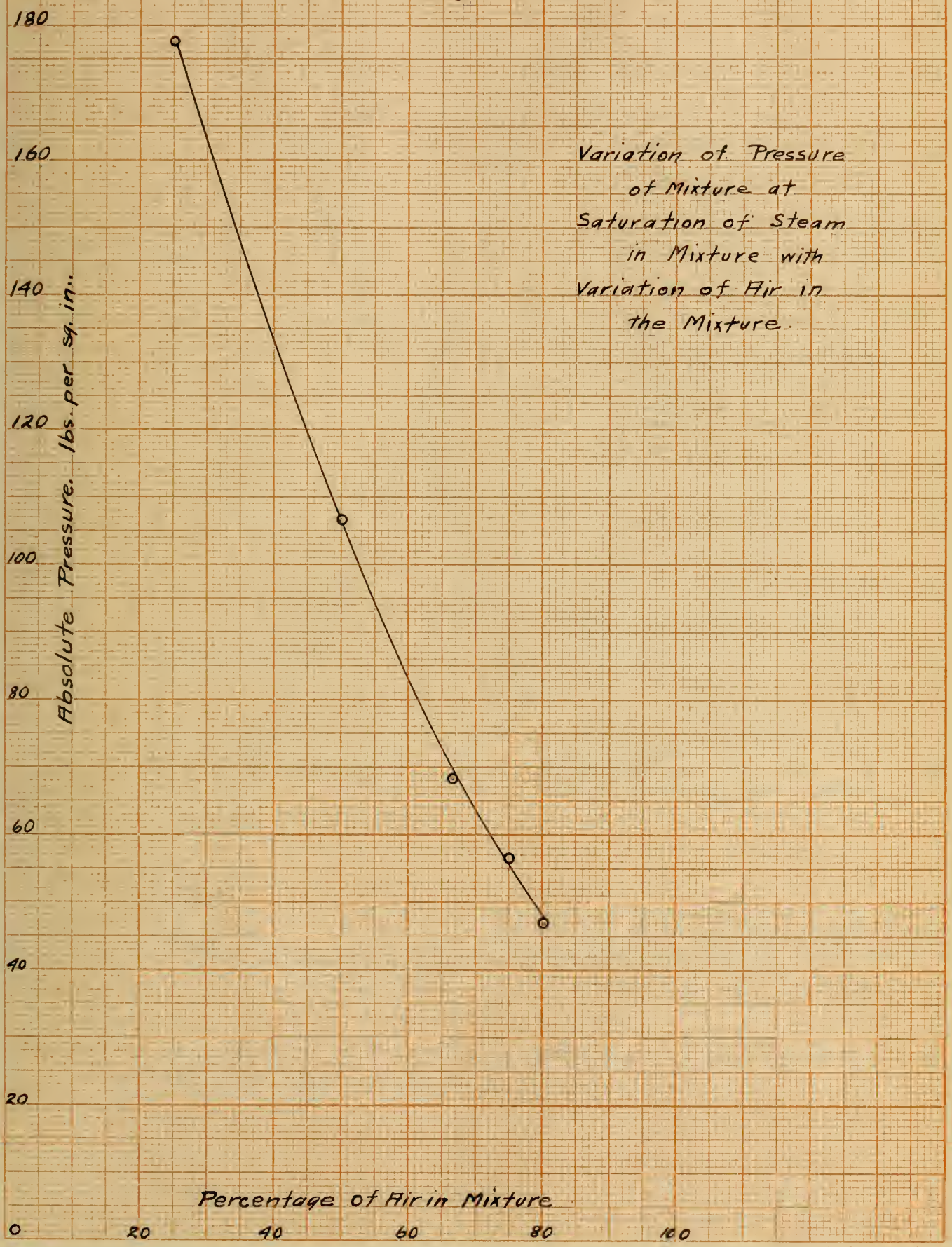


Fig. 4.

Variation of Temperature of Mixture of Saturation of Steam in Mixture with the Variation of Air in Mixture.

U. OF I. S. S. FORM 3

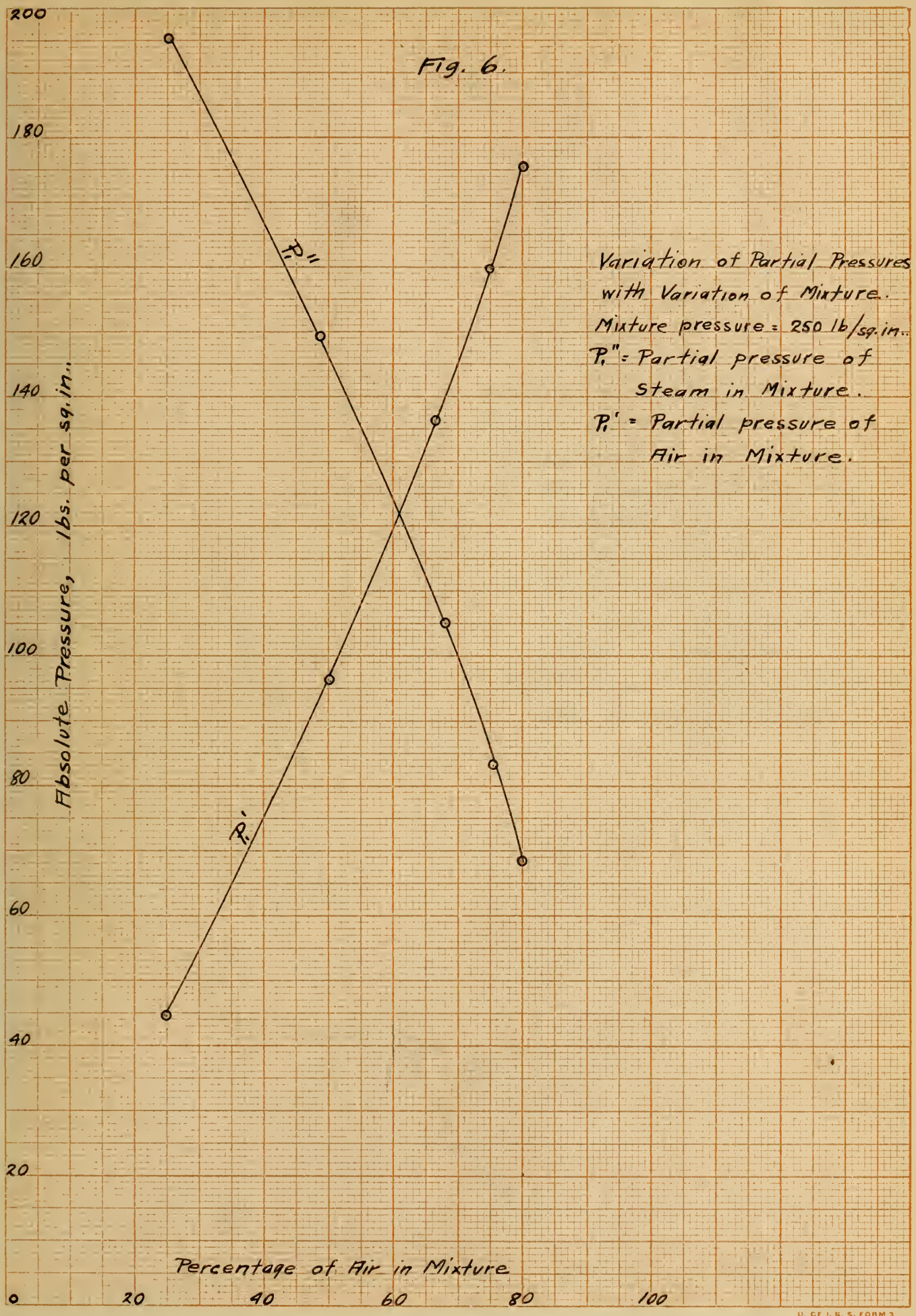
Fig. 5.



Variation of Pressure of Mixture at Saturation of Steam in Mixture with Variation of Air in the Mixture.

U. OF I. B. S. FORM 3

Fig. 6.



Variation of Partial Pressures with Variation of Mixture.
Mixture pressure = 250 lb/sq. in.
P_1'' = Partial pressure of Steam in Mixture.
P_1' = Partial pressure of Air in Mixture.

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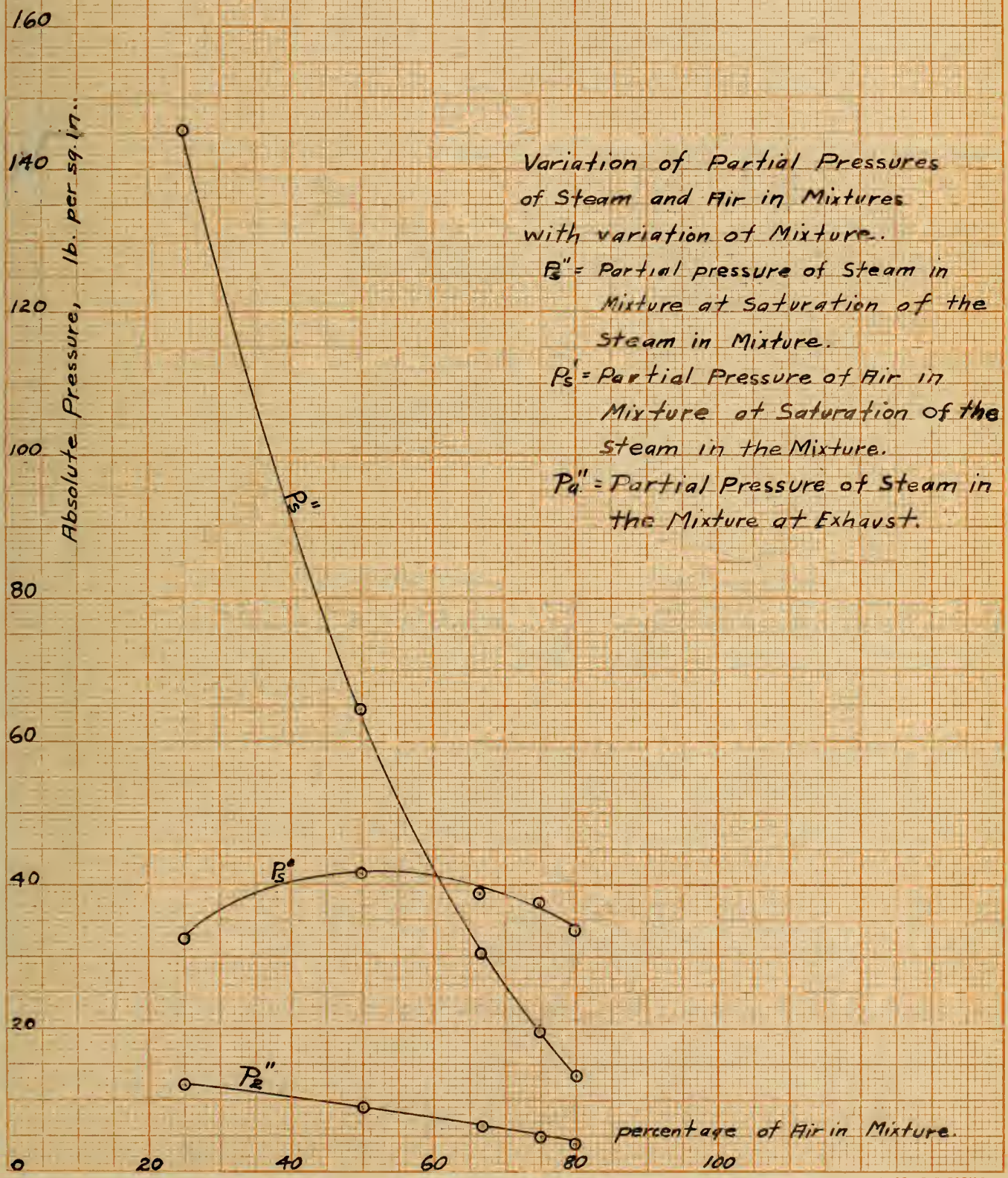
Fig. 7.



Variation of Partial Pressures of Steam and Air in Mixtures with variation of Mixture.

P_s'' = Partial pressure of Steam in Mixture at Saturation of the Steam in Mixture.

P_s' = Partial Pressure of Air in Mixture at Saturation of the Steam in the Mixture.

P_4'' = Partial Pressure of Steam in the Mixture at Exhaust.

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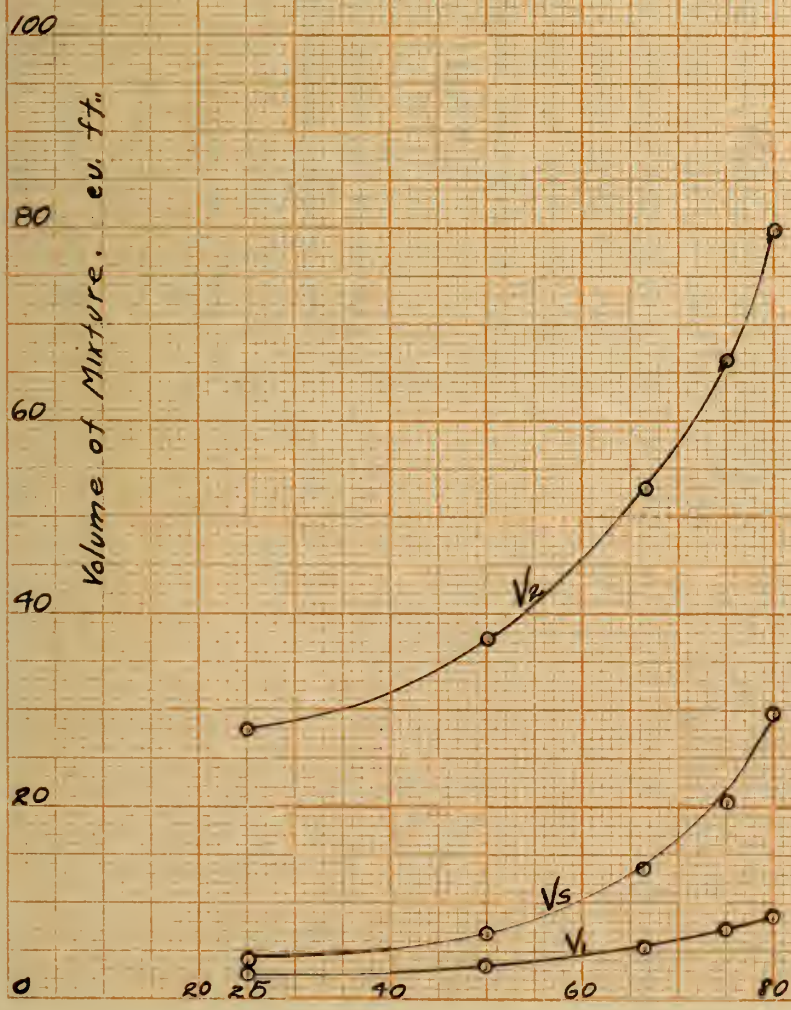
Fig. 8.

Variation of Volume of Mixture
with
Variation of Air in Mixture.
(Percentage of Air based on
1 lb. of Steam).



U. OF I. S. S. FORM 3

Fig. 9.

Figs. A.

Ideal Engine Cards
for
Steam and Air Mixtures.

—— Full line, 50% Air Mixture.
---- Dotted line, 80% Air. Mixture.
◎ Double Circle indicates the point where saturation of Steam in Mixture occurs.

Fig B.

Card showing difference in Area of two cards in Figs. A. Compression line in Fig A. drawn Vertically in Fig B. Horizontal Difference between Compression and Expansion lines of Fig. A laid of horizontally from Vertical Compression line in Fig B.

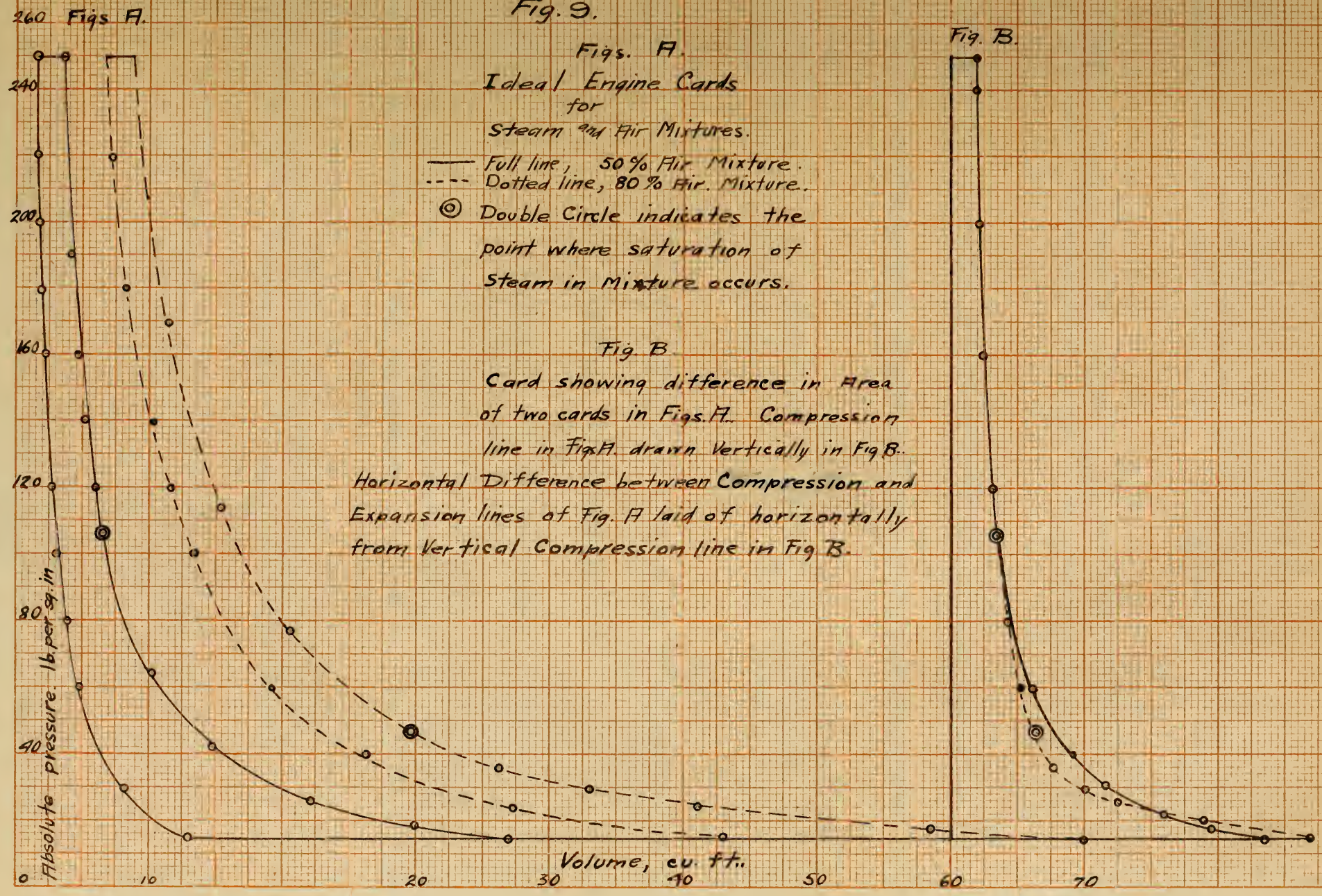
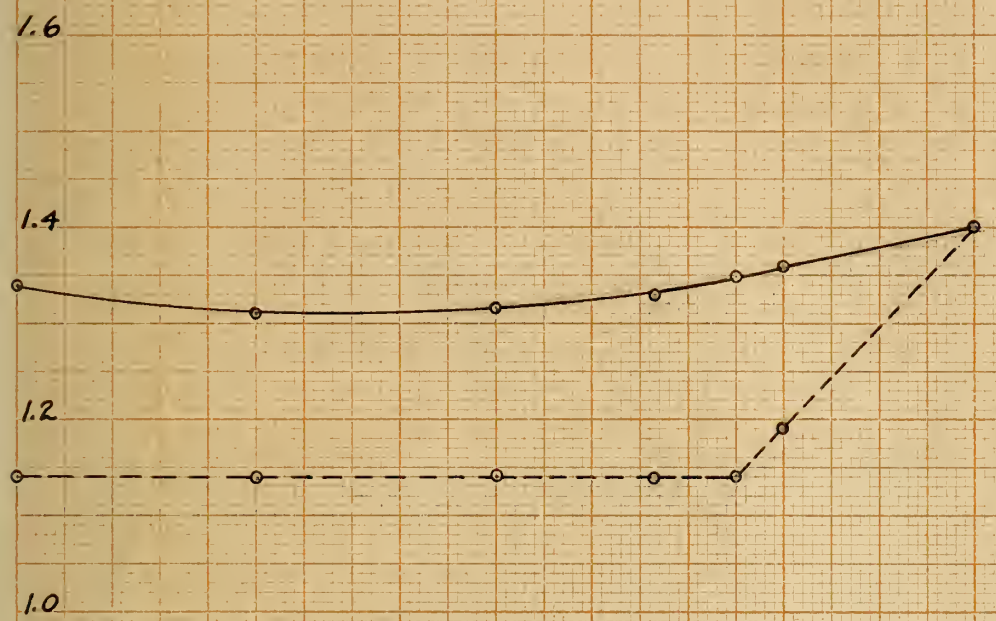


Fig. 10.



Variation of Exponent n
with
Variation of Percentage
of Air in the Mixture.
—— Steam in the Mixture
is above Saturation.
--- Steam in Mixture
is below Saturation.

Percentage of Air in the Mixture.

0 20 40 60 80 100

U OF I B S FORM 3

Logarithmic E
for
Steam and A

In every curve,
in the mixture is
of Air in the Mixtur
curve.

The double circle
where saturation o
mixture occurre

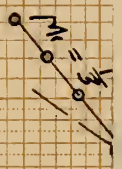
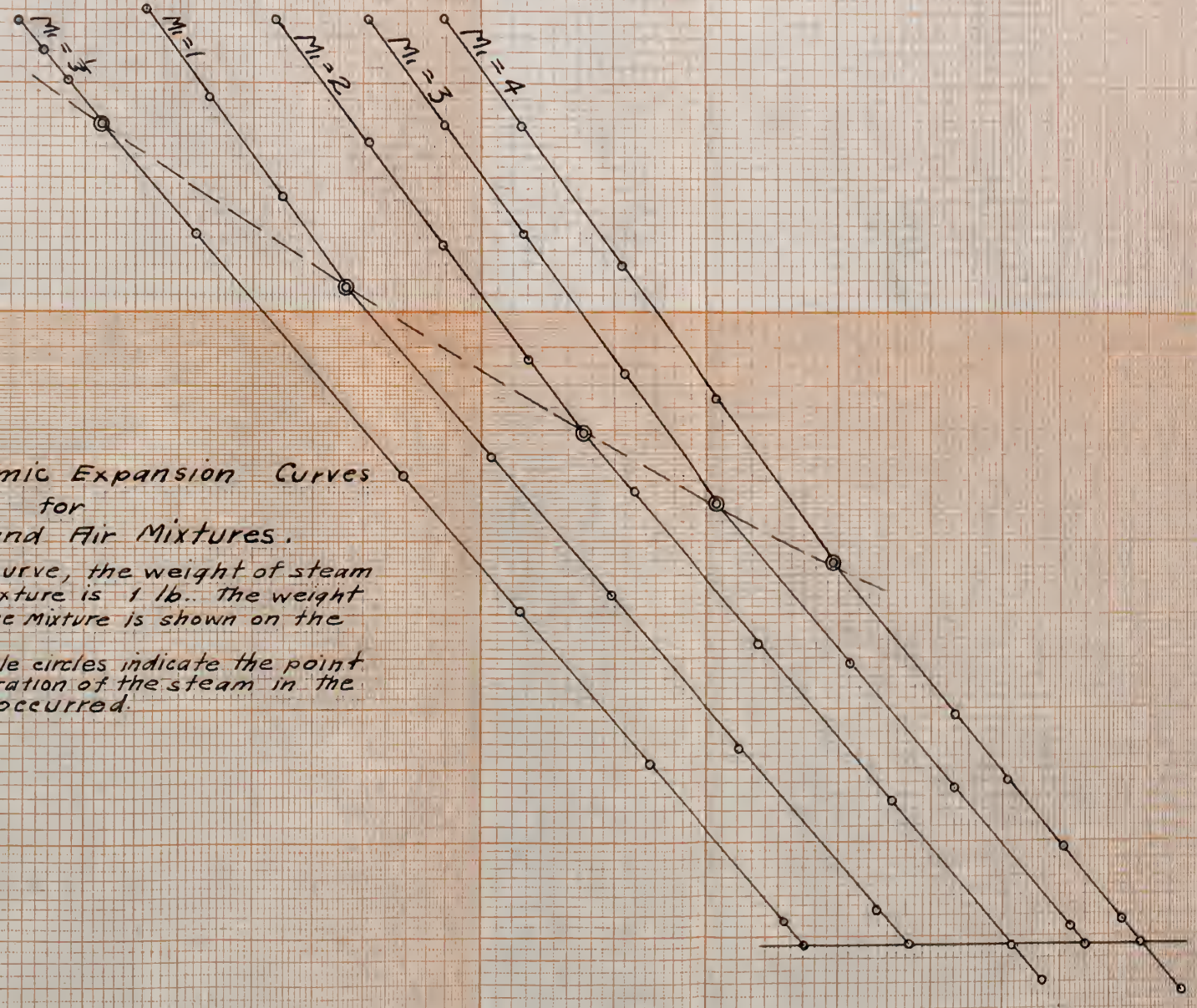


Fig 11.



Logarithmic Expansion Curves for Steam and Air Mixtures.

In every curve, the weight of steam in the mixture is 1 lb. The weight of Air in the Mixture is shown on the curve.

The double circles indicate the point where saturation of the steam in the mixture occurred.

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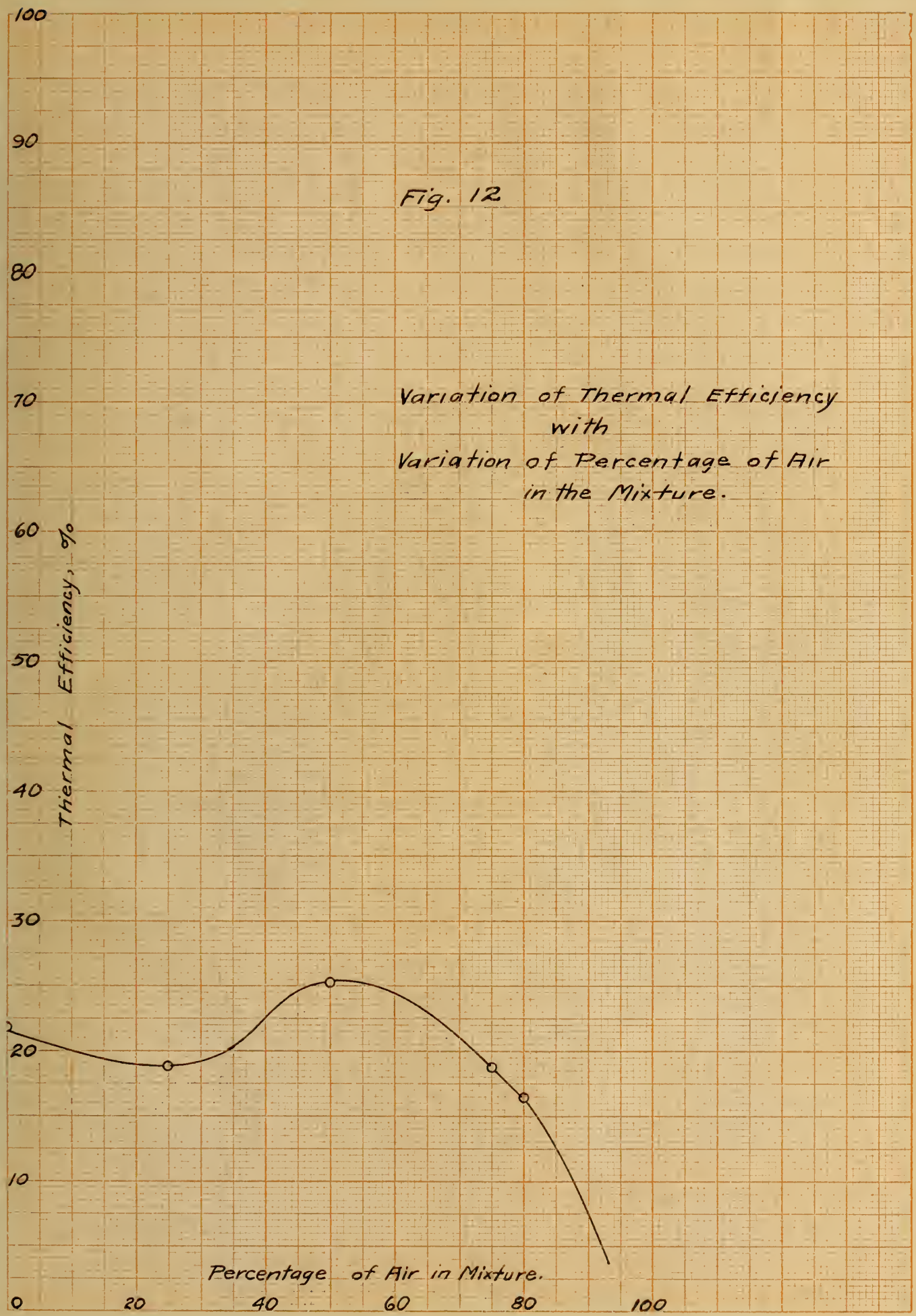
Fig. 12

Variation of Thermal Efficiency
with
Variation of Percentage of Air
in the Mixture.



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